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## TRANSLATION

PRINCIPLE OF THE MOLECULAR AMPLIFIER AND GENERATORS  
OF COHERENT LIGHT

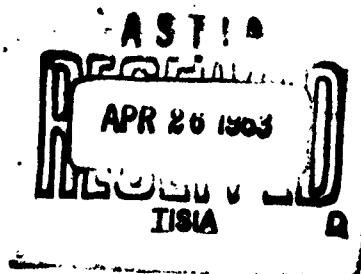
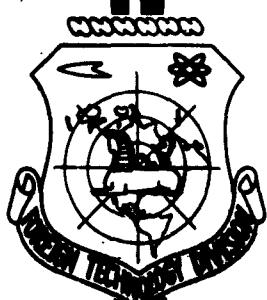
By

B. M. Yavorskiy

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# UNEDITED ROUGH DRAFT TRANSLATION

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COHERENT LIGHT

BY: B. M. Yavorskiy

English Pages: 13

SOURCE: Russian Periodical, Svetotekhnika, Nr 2,  
1962, pp 1-5

S/196-62-0-12

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PRINCIPLE OF THE MOLECULAR AMPLIFIER AND GENERATORS OF COHERENT LIGHT

by

B. M. Yavorskiy

In the last two years there have appeared sources of light new in principle, which possess unusual properties. Abroad these sources of light are called optical masers or lasers, but more correctly one should call them generators of coherent light (GKS).

The scheme of the generators of light is based on the use of the principle of molecular amplification of electromagnetic waves. The principle of the molecular amplifier in turn is based on the use of the phenomenon of forced (induced or stimulated) emission, theoretically predicted by A. Einstein as far back as 1917 [1].

Forced Emission and the Principle of Molecular Amplification Let us consider two of some kind of legitimate energy states of the atom or molecule. As is generally done we will portray these states on a diagram in the form of horizontal straight lines which correspond to different levels of energy (Fig. 1). Atoms can pass from one level to another (from one state into the other) as the result of various processes. The term optical processes is used for processes which are accompanied by the emission or the absorption of electromagnetic radiation.

Up to Einstein's time one talked about only two optical processes: spontaneous emission and absorption. In spontaneous emission the atom passes from a higher level to a lower one and the excess of energy is given off in the form of the energy of photons hurled away from it. According to modern interpretations the spontaneous transitions are brought about by the so-called quantum neutral oscillations of an electromagnetic field.

In the processes of absorption the atom absorbs a photon and passes from a lower energy level to a higher one.

The atom can give off and absorb only photons corresponding to an emission with a frequency  $\gamma$ , determined by Bohr's known relationship

$$\hbar\gamma = E_2 - E_1 \quad (1)$$

where  $\hbar\gamma$  is Planck's constant, and

$E_1$ ,  $E_2$  are the energies of the atom in the first and second states.

Einstein showed that there should be a third process—forced or stimulated emission. This process is brought about only by photons which satisfy the relationship (1).

The photon flying past an atom which is in the upper energy level  $E_2$  as it were knocks it down to the level  $E_1$ . In this case the atom gives off the excess of its energy just as in the spontaneous process in the form of the energy of a new photon. In this way the further flight consists of two photons.

Einstein showed that the forced emission should be completely identical in its parameters with the forcing emission. The new photon has the same energy and flies strictly in the same direction as the photon which stimulated its emergence. In wave-theory language the effect simply amounts to an increase in the amplitude of a passing wave without change in its frequency, direction of its propagation, phase, and polarization. The forced radiation is coherent with the forcing radiation. Einstein introduced the possibility of three optical processes:

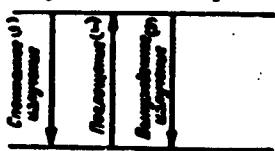


Fig. 1 Key: (1) spontaneous emission;  
(2) absorption; (3) forced emission.

$A_{21}$  probability of spontaneous emission;  $B_{12}\rho\gamma$  probability of absorption, where  $\rho\gamma$  is the volumetric density of the absorbed emission;  $B_{21}\rho\gamma$  probability of

forced emission.

He also showed that

$$B_{12} = B_{21}; \quad (2)$$

$$\frac{A_{12}}{A_{21}} = \frac{8\pi h\nu^3}{c^5}. \quad (3)$$

In the passing of radiation through a layer of substance the processes of absorption will diminish and the processes of forcing emission will increase its intensity at the expense of additional photons emitted by the atoms. It is possible to show that the index of absorption of the medium  $K$  satisfies the relationship (3):

$$K = \frac{h\nu}{c\Delta\nu} (B_{12}N_1 - B_{21}N_2), \quad (4)$$

where  $\Delta\nu$  is the dispersion by frequencies which characterizes the sharpness of the resonance;

$N_1$  is the concentration of atoms at the level  $E_1$ ;

$N_2$  is the concentration of atoms at the level  $E_2$ .

By making use of (2) we will get:

$$K = \frac{h\nu}{c\Delta\nu} B_{21}N_1 \left( 1 - \frac{N_2}{N_1} \right). \quad (5)$$

Ordinarily  $N_2$  is less than  $N_1$ , and therefore the index of absorption is positive. The processes of absorption prevail over the processes of forced emission.

The flux of emission  $F$  is weakened in passing through a layer of substance of the thickness  $L$  according to the known Bouguer's law:

$$F = F_0 e^{-KL}. \quad (6)$$

Such a weakening in the intensity will be observed, in particular, in all media which is in thermodynamic equilibrium. In equilibrated conditions

$$\frac{N_2}{N_1} = e^{-\frac{E_2 - E_1}{kT}}; \quad (7)$$

Here  $k$  is Boltzmann's constant;

$T$  is the absolute temperature.

In the period 1939—1940 V. A. Fabrikant [2] for the first time

called attention to the possibility of obtaining a medium with a negative coefficient of absorption  $K$ . According to (5) to do this it is sufficient to fulfill the inequality

$$\frac{N_2}{N_1} > 1. \quad (8)$$

The inequality (8) clearly can be obtained from (7) only at negative absolute temperatures, since  $E_2 > E_1$ . This signifies that the inequality (8) is attainable only under unequilibrated conditions when (7) is essentially no longer applicable. For maintaining a medium in a state of inequilibrium corresponding to (8) it is necessary to excite it from an extraneous source of energy. In [2] there was pointed out a concrete method for obtaining plasma of a gas discharge with negative index of absorption. "The latter has not yet been observed a single time in a discharge notwithstanding the fact that such a relationship in principle can be accomplished (Perm. B. Ya.) .... It seems to us that a realistic but difficult way of obtaining the necessary conditions is the use ... of molecular admixtures for breaking down the lower levels. In such experiments we will obtain an intensity of the emitted radiation greater than the incident one (Perm. B. Ya.) ... and it would be possible to speak of direct experimental proof of negative absorption" [2].

Actually in this case Bouguer's law takes on the form [3 and 4]:

$$F = F_0 e^{(K+L)}, \quad (9)$$

and the intensity of emitted radiation  $I$  is greater than  $I_0$ .

The relationship (9) is a generalization of Bouguer's law to media with a negative index of absorption. The law of Bouguer and Fabrikant (9) describes the avalanchelike increase in intensity in proportion to the dispersion of a beam in a medium. In this way in the paper [2] there was given the first preliminary formulation of a new principle of amplification, later called the principle of molecular amplification.

However, up to 1951 experiments were carried on solely for the purpose of proving the existence of induced radiation. In 1951 the question arose about the practical use of media with negative index of absorption. The general formulation of the principle of molecular amplification for a broad range of electromagnetic radiations was given by V. A. Fabrikant, M. M. Budynskiy, and F. A. Butayeva in an authorship claim under No. 576,749/26 under date of June 18, 1951 [4]. In the description of the invention for the certificate of authorship No. 123,209 issued on this application of a "Method of amplifying electromagnetic radiation (ultraviolet, visible, infrared, and radio-range waves)" it is stated:

"There is proposed a method of amplifying electromagnetic radiation based on the phenomenon of induced emission theoretically developed by A. Einstein in 1917. With the proposed method of amplification there does not occur a conversion of the amplifiable energy into other kinds of energy. The method is suitable for amplifying ultraviolet, infrared, and radio-range waves.

"For accomplishing the described method of amplification there is created a medium which has a negative coefficient of absorption of radiation. The intensity of the flux of radiation passing through such a medium increases, which produces the effect of amplification. A medium with negative index of absorption is created at the expense of an inequilibrated dispersion of the particles of the medium (for example, atoms or molecules) as to their energy states. The concentration of particles on the upper energy states should exceed (taking into account the statistic weights) the concentration of particles on the lower energy states."

Further in the description of the invention there are considered some methods of obtaining inequilibrated distributions of particles according to their energy levels used at the present time for the creation of masers

and lasers. The subject of the invention was formulated in the following way:

"A method of amplifying electromagnetic radiation (ultraviolet, visible, infrared, and radio-range waves) which is distinguished by the fact that the amplifiable radiation is passed through a medium in which with the aid of auxiliary radiation or by another way there is created a concentration, excessive in comparison with an equilibrated one, of atoms, other particles, or systems of the latter on the upper energy levels."

The first molecular generators of radio waves using the principle of molecular amplification were created by N. G. Basov and A. I. Prokhorov [5] and also by Gordon, Zeiger, and Townes [6] in 1954.

Although the power of the molecular generators was exceedingly small— $10^{-10}$  w, their creation proved to be the push for rapid development of a new branch of technology—quantum radio technology.

Generators of Coherent Light By making use of the formulas (3) and (5) one can compare the radio range and the optical range from the point of view of the possibilities for using the principle of molecular amplification.

It is clear that spontaneous transitions are not suitable for the purposes of molecular amplification. These transitions reduce the number of atoms  $N_2$  on the upper level and thereby make more difficult the accomplishment of inequality (8). At the same time the probability of spontaneous transitions  $A_{21}$ , according to the formula (3) is proportional to the cube of the frequency. The frequency of radio waves even of the ultrashort range is so low that  $A_{21}$  is practically equal to zero. For visible light the frequency is greater by five orders, correspondingly  $A_{21}$  by fifteen orders (by  $10^{15}$  times!) greater (for permissive transitions  $A_{21} = 10^7 - 10^8 \text{ sec}^{-1}$ ). The infrared range is in a somewhat better position.

In spite of the difficulties pointed out, F. A. Butayeva and V. A. Fabrikant [5] accomplished a medium with negative coefficient of absorption in mercury vapors excited by a glow discharge. The research was done on the lines of a visible mercury triplet with wave lengths 546.074; 4358.34 and 4046.56 Å. For selective breakdown of the lower levels, to the mercury there was added molecular hydrogen with a pressure of some millimeters on the mercury column. As a result  $N_2$  on the upper level became more than  $N_1$  of the concentration on the lower levels, and amplification was obtained on the two upper lines of the triplet, respectively, equal to 1.14 and 1.1. On the line 4046.56 Å no amplification was observed. V. K. Ablekov, M. S. Pesin, and I. L. Fabelinskij [7] accomplished a medium with negative absorption with the aid of selective excitation of atoms up to the upper level. A gas discharge was effected in a mixture of vapors of mercury and zinc. An amplification was observed for the red line of zinc with a wave length of 6.362 Å. The upper level of this line is close to one of the levels of the atom of mercury, which creates the possibility of selective excitation of this level of zinc with collisions between the excited atoms of mercury and the normal atoms of zinc with transmission of energy from the atoms of mercury to the atoms of zinc, since of the first in the discharge it was greater than of the latter. The authors obtained a change in the transparency of the me-

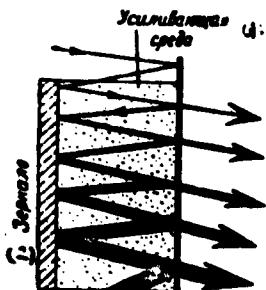


Fig. 2. Key: (1) amplifying medium;  
(2) mirror.

dium for the line 6.362 Å under different conditions of from 1.5 to 10.

Further, in the application of V. A. Fabrikant, M. M. Bulynskij, and F. A. Butayeva [4] it was pointed out that the effect of amplification can be increased many times by passing

an amplifying signal through one and the same layer of the amplifying medium. This can be attained by putting the layer of the medium between two mirrors. In 1958 A. N. Prokhorov [8] and some time later Schawlow and Townes [9] showed that the use of such a device can lead to the transition from the process of amplification to the process of generation. For this it is sufficient that the coefficient of the reflection of mirrors  $\rho$  satisfy the obvious condition

$$\rho_e^{(K)} > 1. \quad (10)$$

i. e., the losses in the mirror should be less than the amplification in the medium.

Besides, the mirrors should be sufficiently flat (plane) and set parallel to each other.

If between such mirrors one puts a medium with negative absorption then any photon arising in this medium at the expense of spontaneous emission of atoms and proceeding in a direction close to the normal to the two mirrors will bring into existence a whole avalanche of photons (Fig. 2). The closer the direction of the propagation of the photon is to the normal the greater the amount of reflection which the beam will undergo before it goes away at the edge of the mirror. Therefore only rays close to the normal undergo great amplification. If one of the mirrors is made somewhat transparent then through it there bursts a directed pencil of light rays of great brightness. All these rays will be coherent. In principle the limit of the power of the beam is determined in the given case by the power brought to the excitation of the medium. In principle the limit of the angular flare of the beam is the diffraction on the mirrors. If the mirrors have a diameter of the order of centimeters, then the limiting angular flare for the visible rays will be of the order of  $10^{-5}$ . With a dimension of the mirrors of the order of meters it will be  $10^{-7}$ . The solid angles, respectively, are

This great directivity proves to be the basic advantage of the optical range as compared with the radio range. The great directivity makes realistic the attaining of ranges of action of the order of  $10^{13}$ — $10^{14}$  km, i. e., ranges on an astronomical scale.

A generator of coherent radiation of practical interest was created by Mainman [10] with a solid as the active medium. The amplifying medium is rubin, the crystal of aluminum oxide  $\text{Al}_2\text{O}_3$  with an admixture of chromium oxide  $\text{Cr}_2\text{O}_3$ , ordinarily in the amount of 0.05 to 0.5%.

The priority in the use of rubin for microwave generators belongs N. G. Basov and A. M. Prokhorov. A series of investigations of the optical properties of rubin was done by N. A. Tolstyy and P. P. Geofilov [11].

The active substance in rubin are the ions of chromium  $\text{Cr}^{4+}$ . The energy system of the levels of  $\text{Cr}^{4+}$  contains two broad energy bands closer to the basic level and a double metastable level the transitions from which to the basic level correspond to the wave lengths of red light, 6,929 and 6,943 Å (Fig. 3). With intense radiation of the rubin by green light from a powerful pulse lamp designed with neon and krypton there occurs a transition of ions onto the levels of the broad band, whence it is very probable that there is a transition of ions without radiation onto the double level with the emission of the excess of energy of the crystalline lattice of the rubin. In this way it is possible to create conditions under which the density of the double level will be greater than the density of the basic level and obtain a generator on the resonance lines 6,929 and 6,943 Å. The advantage of rubin consists in the presence of a broad band of absorption for green rays corresponding to a broad energy band. This makes it possible to introduce into the rubin great excitation power. Along with this situation the red lines do not have great width, which assures good conditions for their am-

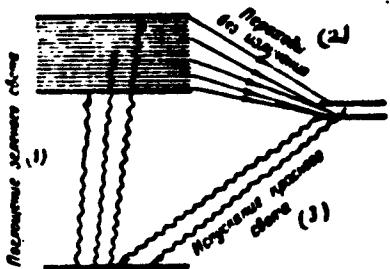


Fig. 3. Key: (1) absorption of green light; (2) transitions without radiation; (3) emission of red light.

plification. Little  $\Delta\nu$  according to the formula (5) corresponds to large K.

In the generator of coherent red light on the line 6,943 Å there was used a cubic crystal of rubin wound around by a pulse pumping tube. The pumping tube radiated powerful pulses of light in thousands of kilo watts with a length of about 1 millisecond

and a frequency of repetition of 1 pulse 30—60 sec, limited by the heating of the tube. In the crystal of rubin there was created a pulse of red coherent radiation with a spectral width  $\Delta\nu$  in 1 Å, angular divergence of 0.01°, and an instantaneous power of the order of 10 kw. The power average in time of the red beam amounted to 20 kw. In the perfected rubin generator of the Bell concern, together with the rubin cube, there was used a little rubin cylinder with mirror bases. During the course of the pumping time 1 msec the crystal emitted by sparks of the length of 1  $\mu$ sec (with intervals of 5—10  $\mu$ sec, depending on the power of the pumping) a narrow monochromatic beam of red color.

In accordance with the work of Maiman there is being done interesting development of generators of visible and infrared radiation with crystals of calcium fluoride and admixtures of uranium or samarium, which enable one to lower the power of excitation by a factor of 500—1,000, as compared with rubin. A generator of infrared radiation with a wave length of 2.49 microns was made on the basis of a crystal of fluorite of calcium with a content of 0.05% of uranium admixture. To the emission of 2.49 microns there corresponds the transition of ions of  $U^{++}$  from the metastable level to the intermediate

level located below. With extreme chilling this intermediate level is less in density by a factor of  $10^{10}$  than the basic energy level. Therefore, with the aid of the pumping tube (with a power less by a factor of 500 than for the rubin generator) there can be assured the necessary shifting of ions onto the metastable level.

The shortcoming of generators with crystals is the pulse system of their working. The use of gaseous mixtures described above make it possible to design generators of continuous action. In the paper by V. A. Fabrikant [12] there is given a general analysis of the gaseous mixtures for these purposes.

For the creation of a generator of infrared radiation as an amplifying medium there is used the plasma of a high-frequency gas discharge in a mixture of helium with neon with a pressure of helium exceeding by ten times the pressure of neon [13]. Through the action of excitation shocks of electrons the atoms of helium pass into the excitation state. In the collision of excited atoms of helium with atoms of neon, the latter are also excited and pass to one of the four upper levels of neon, located close to the corresponding level of helium. The transition of atoms of neon from these levels onto one of the lower levels (altogether there are 10 intermediate energy levels) is accompanied by radiation in the range from 0.9 to 1.7 microns. The infrared sharply directed beam possesses in this situation complete monochromatic quality. The power in the beam is 0.1 w.

The data of the first devices are very far in principle from the possible results. In principle it is possible to obtain powers of beams to which would correspond light pressure of the order of a million atmospheres. The monochromatic quality makes it possible to transmit a great volume of information. All this creates boundless prospects for the use of amplifiers and generators of coherent light.

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